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GRID INTERACTIVE PV SYSTEM WITH FUZZY LOGIC CONTROLLER BASED ACTIVE POWER FILTER

RESHMA B KANDEKAR[1], D ARCHANA[2] & A PRASADA RAO[3]

[1]PG Student, Department of EEE, VITAM College of Engineering, Visakhapatnam, Andhra Pradesh, India

[2]Assistant Professor, Department of EEE, VITAM College of Engineering, Visakhapatnam, Andhra Pradesh, India

[3]Associate Professor, Department of EEE, VITAM College of Engineering, Visakhapatnam, Andhra Pradesh, India

ABSTRACT

Recently, the energy crisis in the world has led to the rise in use of renewable energy sources. With the advancement in power electronics technology, the solar photovoltaic energy has been recognized as an important renewable energy resource because it is clean, abundant and pollution free. The two stage grid interactive PV system described in this paper supplies active power as well as provides harmonic and reactive power compensation. This additional feature increases the effective utilization of PV inverter and increases the overall efficiency of the system. The current paper proposes an intelligent control method for the maximum power point tracking (MPPT) of a photovoltaic system under variable insolation conditions. Here in this paper, intelligent control method uses a Fuzzy Logic Controller applied to a DC-DC converter device as well as Dc Link Controller to achieve the DC Link Voltage Constant.

KEYWORDS: Maximum Power Point Tracking (MPPT), Fuzzy Logic Controller, Reactive Power Compensation, PV Module

INTRODUCTION

Harmonic current compensation by means of active power filter (APF) is a well-known effective solution for the reduction of current distortion and for power quality improvement in electrical systems. The shunt compensator behaves as a controlled current source that can draw any chosen current references which is usually the harmonic components of the load currents. Meanwhile, more and more APFs are applied not only in harmonic current and reactive power compensation but also in the neutral line current compensation, harmonic damping application, and power flow control. As Figure 7 shows, in the power quality improvement, the APF could be installed in the source side or near the load side and it could even be integrated into the load-front converter (such as the input stage converter of variable-speed drives).Introducing APF technology to resolve the power quality issues catches increasing attention. Several papers have been published about the APF's application in the power quality since 2005. Shunt active power filters provide an effective solution for the harmonic elimination and the improvement of the power quality in this kind of system. The shunt active filter works as a controlled current source which injects into the grid an amount of harmonic current equal to the one drawn by the distorting loads. A PV based MPPT control system is implemented so that the active filter injects a current which follows the DC link voltage controller, corresponding to the harmonic content of the load.

It is well known that a PV module consists of several PV cells connected in series in order to ensure a useful output voltage level. Assuming that the cells are identical, this level is calculated by summing each cell voltage. The functioning parameters [5] of the module depend mainly on the solar irradiance and on the cells temperature, as well as on the semiconductor material properties. For each meteorological condition there is a maximum power point (MPP) at which the system must work in order to deliver the optimal power to its load. The objective of the maximum power point

trackers (MPPT) is to make the system [2] work in this point or near. The functioning point of the system is the intersection between the module I-V curve and the load curve. One of the major concerns in the power sector is the day to day increasing power demand but the unavailability of enough resources to meet the power demand using the conventional energy sources.

Utilization of renewable energy resources is the demand of today and the necessity of tomorrow. With advancement in power electronic technology, the solar photovoltaic energy has been recognized as an important renewable energy resource because it is clean, abundant and pollution free.[11] The extraction of maximum available power from a photovoltaic module is called Maximum Power Point Tracking and is done by Maximum Power Point Tracking Controller. The efficiency of the photovoltaic system may be substantially increased by using Maximum Power Point Tracker (MPPT). A number of algorithms are developed to track the maximum power point efficiently. Among all MPPT [11]-[4] methods, Perturb and Observe (P&O) method and Incremental Conductance method are most commonly used. Most of the existing MPPT algorithms [3] suffer from the drawback of being slow tracking. Due to this the utilization efficiency is reduced. The incremental conductance technique gives good performance under rapidly changing environment conditions but has complexity in implementation. The constant voltage and constant current techniques are simple but they do not track the MPP accurately. The β-method gives good performance and [10] higher tracking efficiency but has complex calculations and depends on accurate β-factor. Fuzzy logic is becoming popular for MPP tracking which overcomes the disadvantages of conventional methods. The MPPT control using fuzzy logic is simple to implement, gives better convergence speed, and improves the tracking performance with minimum oscillation. Many stand alone PV system and two-stage grid connected PV system use fuzzy logic controller for MPP that takes at least two inputs and generates the control output. The fuzzy logic MPPT used in [6] controls the duty ratio of the DC-DC [8] converter in standalone system using change in slope of P-V curve as input and change in voltage as output. The authors in proposed fuzzy logic controlled modified Hill Climbing method for MPP tracking in micro-grid stand-alone PV system. The algorithm generates change in duty ratio as an output with change in power and change in current as input. The two stage grid interactive PV system described in this paper supplies active and reactive power as well as provides the harmonic compensation during day time[6]-[2]. At night, the PV inverter still provides harmonic and reactive power compensation. Thus, the overall utilization of PV system is increased. The simulation results obtained using proposed algorithm gives the validity of the grid interactive PV system for reactive power and harmonic compensation features in addition to active power injection.

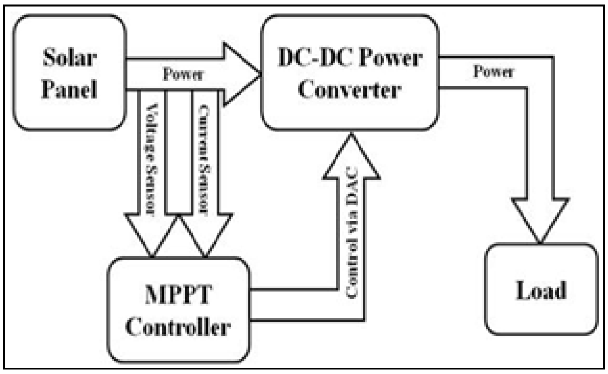

Figure 1: Block Diagram of MPPT

PV ARRAY MODELLING AND CHARACTERISTICS

The power that one module can produce is seldom enough to meet requirements of a home or a business, so the modules are linked together to form an *array*. Most PV arrays use an inverter to convert the DC power produced by the modules into alternating current that can power lights, motors, and other loads. The modules in a PV array are usually first connected in series to obtain the desired voltage; the individual strings are then connected in parallel to allow the system to produce more current The PV array is made up of number of PV modules connected in series called string and number of such strings connected in parallel to achieve desired voltage and current. The PV module used for simulation study consists of 36 series connected polycrystalline cells.

PV Model

The electrical equivalent circuit model of PV cell consists of a current source in parallel with a diode as shown in Figure 2

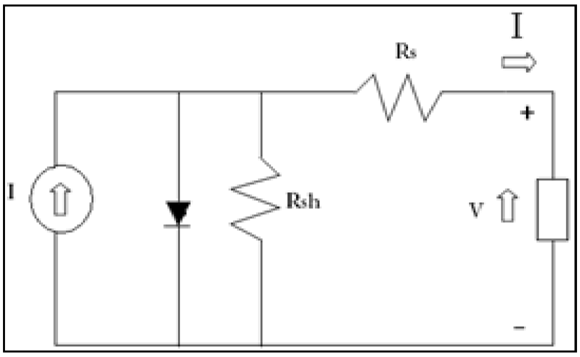

Figure 2: Electrical Equivalent Circuit Model of PV Cell

A Maximum Power Tracking (MPPT) circuit, which allows the maximum output power of the PV array. A Power Factor (PF) control unit, which tracks the phase of the utility voltage and provides to the inverter a current reference synchronized with the utility voltage. A converter, which can consist of a DC/DC converter to increase the voltage, a DC/AC inverter stage, an isolation transformer to ensure that the DC is not injected into the network, an output filter to restrict the harmonic currents into the network. The MPPT algorithm, the synchronization of the inverter and the connection to the grid are discussed. Tracking the DC voltage and current allows MPP calculation which gives the inverter to function efficiently.

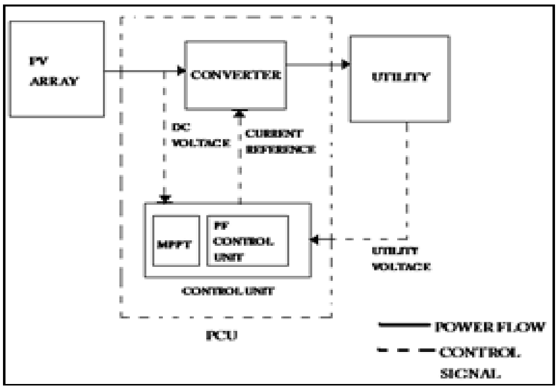

Figure 3: Schematic Diagram of Grid-Connected PV System

From the electrical equivalent circuit of the PV cell, PV output current (*IPV*) is given by

$$\boldsymbol{I_{PV} = I_{ph} - I_D - I_{sh}} \tag{1}$$

Where

$$\boldsymbol{I_D = I_O\left(e^{q\left(\frac{V_{PV}+I_{PV}R_S}{\eta kT}\right)} - 1\right)} \tag{2}$$

And

$$\boldsymbol{I_{sh} = \frac{V_{PV}+I_{PV}R_S}{R_{sh}}} \tag{3}$$

The parameters *q, η, k and T* denote the electronic charge, ideality factor of the diode, Boltzmann constant and temperature in Kelvin respectively. *Iph* is photocurrent, *I0* is diode reverse saturation current, *IPV* and *VPV* are the PV output current and voltage respectively. As the value of *Rsh* is very large, it has a negligible effect on the I-V characteristics of PV cell or array. Thus (1) can be simplified to

$$\boldsymbol{I_{PV} = I_{Ph} - I_O\left(e^{\frac{q(V_{PV}+I_{PV}R_S)}{\eta kT}} - 1\right)} \tag{4}$$

For PV array consisting of Ns series and Np parallel connected PV modules, (4) becomes,

$$\boldsymbol{I_{PV} = N_P\left\{I_{Ph} - I_O(e^{\frac{q(V_{PV}+I_{PV}R_S)}{\eta kT}} - 1)\right\}} \tag{5}$$

PV Characteristics

The PV model is simulated using Solarex MSX60, 60W PV module. The simulated I-V and P-V characteristics of the Solarex PV module at constant temperature and varying insolation are shown Figure 4 respectively. It can be seen from Figure 4 that the decrease in insolation reduces the current largely but voltage fall is small shows that the reduction in insolation reduces the power largely as both voltage and current are decreasing. The effect of temperature on I-V and P-V characteristics of Solarex PV module is shown in Figure 5 respectively. It can be seen from Figure 5 that the increase in temperature reduces the open circuit voltage largely but rise in current is very small. Figure 5 shows that the increase in temperature reduces the PV output power as the reduction in the voltage is larger than the increase in current due to temperature rise.

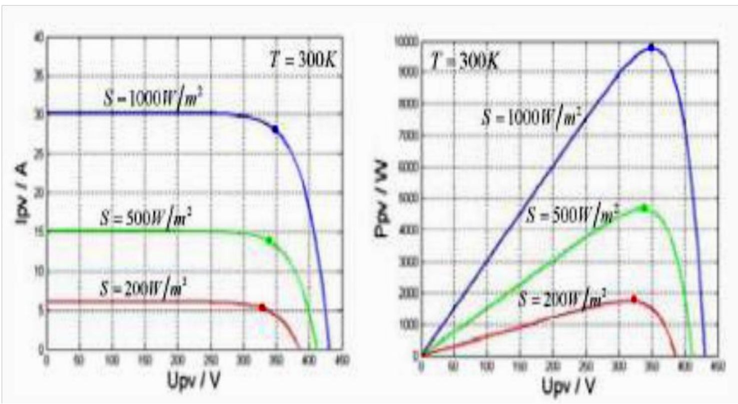

Figure 4: I-V and P-V Curve Obtained for SOLTECH 1STH-235

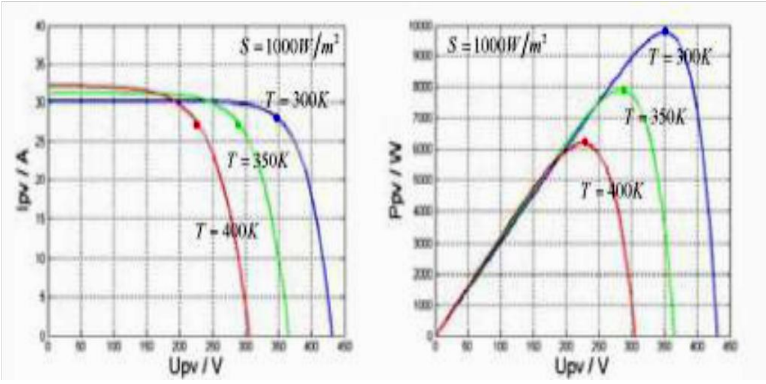

Figure 5: I-V and P-V curve of SOLTECH 1STH-235 at Different Temperatures

PROPOSED MPPT ALGORITHM

From the simulated I-V and P-V characteristics of the PV module, it can be seen that the characteristics are highly nonlinear. Also, there is single point on P-V curve where the PV can produce maximum power. The MPP changes with change in insolation and temperature. Therefore, an MPPT controller is required to extract maximum available power from the PV array under varying load and changing environmental conditions. This paper proposes a novel fuzzy logic based MPPT controller Fuzzy logic can model or control non-linear systems that are difficult to model mathematically. The fuzzy logic is chosen for MPPT as it gives appropriate performance for varying dynamics, higher convergence speed, robust and simple to design compared to conventional methods. The major objective of the proposed controller is to track and extract maximum power from the PV arrays for a varying solar insolation and cell temperature. The block diagram of the proposed fuzzy logic controller (FLC) is shown in Figure 5. The major functional blocks of the FLC are described as follows:

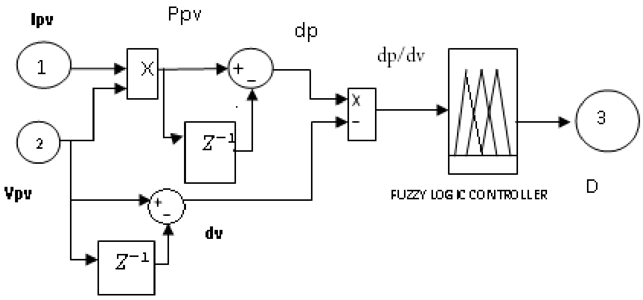

Figure 6: Block Diagram of Proposed Fuzzy Based MPPT Controller

Fuzzification

From the prior knowledge of input and output range, the fuzzification process divides the input and output into linguistic fuzzy sets. The proposed FLC takes single input that is the slope of the P-V curve and gives the duty ratio for switching the boost converter as an output. After sampling the PV array voltage and current, ΔP (k) and

ΔV (k) are determined as follows:

$$\Delta P(K) = P(K) - P(K-1) \quad (6)$$

$$\Delta V(K) = V(K) - V(K-1) \quad (7)$$

Where P(k) and V(k) are the power and voltage of PV array, respectively. The $\Delta P(k)/\Delta V(k)$ obtained using (6) and (7) is given as an input to the FLC that generates the duty ratio (D) as an output for providing the switching pulses to the boost converter in order to operate the PV array at MPP.

Fuzzy Rule Base

The fuzzy rules should be precisely defined based on the knowledge in order to generate an output duty ratio as per the magnitude of the slope of P-V curve to operate the PV array at MPP. When the slope of P-V curve is positive then to reach towards MPP, the duty ratio of boost converter is decreased in order to increase the PV operating voltage. Similarly, if the slope of P-V curve is negative then to move the operating point at MPP, the duty ratio is increased.

Defuzzification

The Defuzzification process generates the single crisp value of output duty ratio (D) from the aggregated fuzzy set that includes a range of output values. The widely used centroid (centre of area) method [16] is used to convert the fuzzy subset of duty ratio (D) to real number. It computes the centre of gravity from the final output fuzzy set, and gives a result which is highly related to all of the elements in the same fuzzy set. It is mathematically represented by

$$\mathbf{Z}^{*} = \frac{\int \boldsymbol{\mu}(\mathbf{z}).\mathbf{zdz}}{\int \boldsymbol{\mu}(\mathbf{z})\mathbf{dz}} \tag{8}$$

where, z* = D which is the output of fuzzy logic controller, ∫ denotes an algebraic integration and z is the aggregated fuzzy set of output The proposed fuzzy logic MPPT controller applies variable steps in duty ratio for controlling the boost converter as per the current operating point and hence, gives faster convergence to MPP compared to conventional algorithms. The proposed algorithm gives robust performance under rapidly changing environmental conditions under which the conventional P&O technique is likely to fail [9].

CONTROL OF GRID INTERACTIVE PV SYSTEM

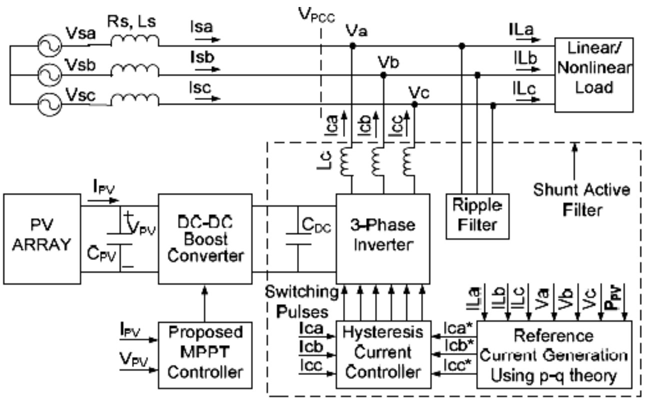

Figure 7: Grid Connected PV System Configuration

The grid interactive PV system configuration used for simulation study is shown in Figure 7. It consists of two power processing stages: DC-DC boost converter as first stage and three-phase voltage source inverter as second stage. The boost converter stage provides not only the boosting of PV output voltage for grid connectivity but also used as MPP tracker.

By controlling the duty ratio of boost converter using the proposed fuzzy based MPPT controller described in section-III, the current corresponding to maximum power is injected into the grid. The second inverter stage is used for

multiple functions: (i) active power injection (ii) harmonic compensation of non linear load connected with the grid and (iii) reactive power compensation of the load. The additional functionality of the PV inverter as a shunt active power filter increases the overall efficiency of the system. The inverter switching signals are generated using the current control technique based on hysteresis current controller.

Reference Current Generation

The reference current generator block generates the reference current to be injected into the grid upon sensing the voltage at the Point of Common Coupling (VPCC) and load currents using instantaneous active and reactive power (*p-q*) theory [17]. For the computation of p and q, the three phase voltages at the point of common coupling (PCC) and load currents must first be transformed to the stationary two axis (α-β) co-ordinates. The instantaneous real and reactive power p and q are determined using equations (9)-(13).

$$\mathbf{V}_{\boldsymbol{\alpha\beta}} = \mathbf{C} \times \mathbf{V}_{\mathbf{abc}} \tag{9}$$

$$\boldsymbol{I_{\alpha\beta} = c \times I_{L\,abc}} \tag{10}$$

$$\boldsymbol{C} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \sqrt{\frac{3}{2}} & -\frac{\sqrt{3}}{2} \end{bmatrix} \tag{11}$$

$$\boldsymbol{p = V_{\alpha} \times I_{\alpha} + V_{\beta} \times I_{\beta}} \tag{12}$$

$$\mathbf{q}{=}\boldsymbol{V_{\alpha} \times I_{\beta} - V_{\beta} \times I_{\alpha}} \tag{13}$$

Both instantaneous power quantities p and q consists of dc and ac components. While the dc components p and q arise due to the fundamental, the ac components p and q are a result of harmonic components. In order to inject active power generated by PV obtained using the proposed MPPT controller and also to provide harmonic as well as reactive power compensation as per the load demand , the reference for active and reactive power are generated according to (14) and (15).

$$\boldsymbol{p^{*} = P_{PV} + \tilde{p}} \tag{14}$$

$$\boldsymbol{q^{*} = q = \overline{q} + \tilde{q}} \tag{15}$$

The ac component $\tilde{p}$ is determined by first extracting □q , using a very low cut off low pass filter and then subtracting it from p obtained using (12). Finally, the reference currents are generated as per (16) and (17).

$$\begin{bmatrix} \mathbf{i}_{\boldsymbol{\alpha}}^{*} \\ \mathbf{i}_{\boldsymbol{\beta}}^{*} \end{bmatrix} = \begin{bmatrix} \mathbf{v}_{\mathbf{s}\boldsymbol{\alpha}} & \mathbf{v}_{\mathbf{s}\boldsymbol{\beta}} \\ -\mathbf{v}_{\mathbf{s}\boldsymbol{\beta}} & \mathbf{v}_{\mathbf{s}\boldsymbol{\alpha}} \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{p}^{*} \\ \mathbf{q}^{*} \end{bmatrix} \tag{16}$$

$$\begin{bmatrix} \mathbf{i}_{\mathbf{ca}}^{*} \\ \mathbf{i}_{\mathbf{cb}}^{*} \\ \mathbf{i}_{\mathbf{cc}}^{*} \end{bmatrix} = [\mathbf{C}]^{\mathbf{T}} \begin{bmatrix} \mathbf{i}_{\boldsymbol{\alpha}}^{*} \\ \mathbf{i}_{\boldsymbol{\beta}}^{*} \end{bmatrix} \tag{17}$$

Hysteresis Current Controller

The hysteresis current controller compares the three phase reference currents (*ica**, *icb**, *icc**) generated using (17) with the actual inverter currents (*ica, icb, icc*) and generates the switching pulses as per the logic given below:

$$\mathbf{if}\ (\boldsymbol{i_{ca} > i_{ca}^{*} + hb})$$

Leg-an upper switch is OFF and lower switch is ON

if $(\boldsymbol{i_{ca}} < \boldsymbol{i_{ca}^{*}} - \boldsymbol{hb})$

Leg-an upper switch is ON and lower switch is OFF

where hb is the hysteresis band around the reference current which is usually 5 % of the maximum current to be injected by the inverter. Similarly, control signals for leg-b and leg-c of the inverter switches are generated.

Ripple Filter

The ripple filter as shown in Figure 8 is used to absorb the switching frequency ripples. The switching ripples are generated due to switching of the inverter using the hysteresis current controller because of practical limitation in minimizing the hysteresis band and also due to switching of the boost converter. The ripple filter is a series R-C filter whose component values are so chosen as to absorb the high frequency components in multiple of switching frequency with the constraint that the fundamental current drawn by ripple filter should not exceed 5 % of the maximum load current.

Membership Functions & Rules

The ΔP(k)/ΔV(k) obtained using (6) and (7) is given as an input to the FLC that generates the duty ratio (D) as an output for providing the switching pulses to the boost converter in order to operate the PV array at MPP. Depending upon the magnitude of the slope of P-V curve, the proposed FLC divides the input and output into seven linguistic fuzzy sets: negative big (NB), negative medium (NM), negative small (NS), zero (ZO), positive big (PB), and positive medium (PM) and positive small (PS). The membership functions of the input and output variables are shown in Figure 8 and Figure 9 respectively. The membership functions for output duty ratio are so chosen that it maintains the dc link voltage higher than 650 V at the same time operate the PV array at MPP. Hence, proposed fuzzy controller eliminates the need for PI controller for dc-link voltage regulation.

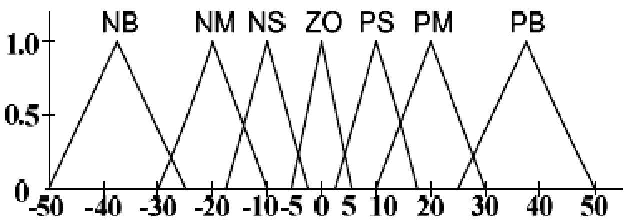

Figure 8: Membership Function for Input Variable (ΔP/ΔV)

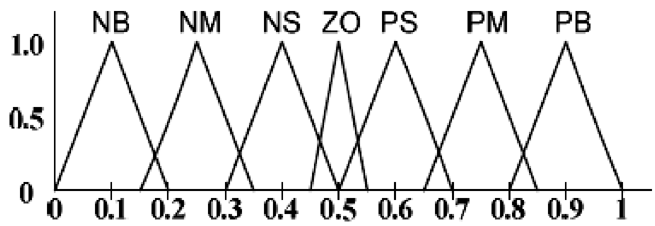

Figure 9: Membership Function for Output Variable (D)

The precisely defined fuzzy logic rules are based on the knowledge to generate an output duty ratio according to the magnitude of slope of PV curve for the operation of PV array at MPP. The slope of PV curve being positive then to reach towards MPP, to increase PV operating voltage, the duty ratio of the boost converter is decreased. In the same way, the duty ratio is increased if the slope of PV curve is negative in order to move the operating point to Maximum power point (MPP). The seven rules used for tracking the MPP in the proposed technique are listed in Table I.

Table 1: Fuzzy Rules

$\Delta P/\Delta V$	NB	NM	NS	ZO	PS	PM	PB
D	PB	PM	PS	ZO	NS	NM	NB

Membership Functions & Rules for DC Voltage controller

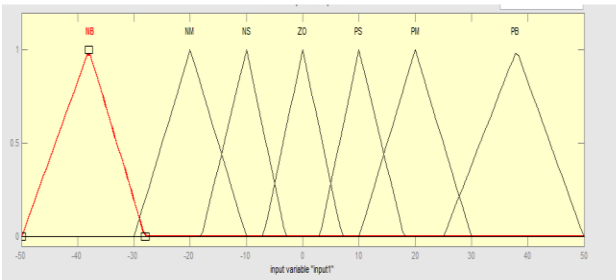

Figure 10: Membership Function for Input Variable

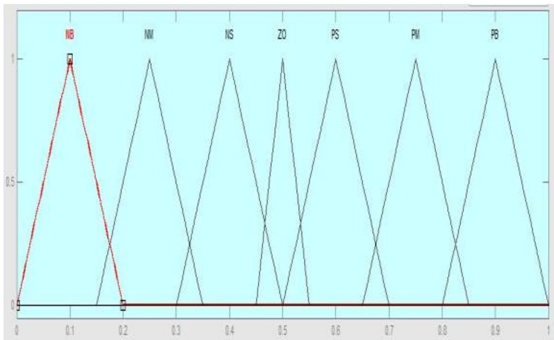

Figure 11: Membership Function for Output Variable

By using these fuzzy rules we can maintain the Magnitude of the DC link capacitor constantly by which the losses in voltage in the capacitor due to the switches can taken from the reference and can be maintained constantly. Due which the system can be effectively controlled.

SIMULATION RESULTS

Here simulation results are carried out under different load conditions as well as various controlling techniques.

- Grid Connected PV System with conventional DC Link Controller based Active Power Filter.
- Grid Connected PV System with proposed Fuzzy Logic Controller based Active Power Filter.

Case 1: Grid Connected PV System with conventional DC Link Controller based Active Power Filter

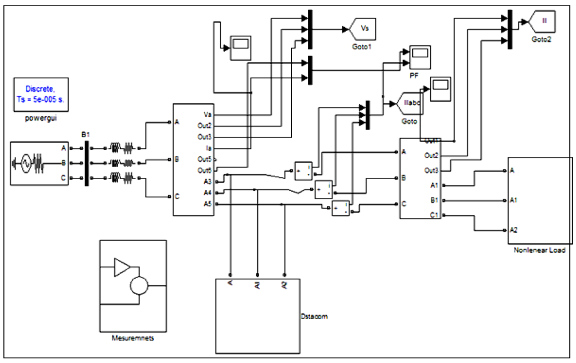

Figure 12: Matlab/Simulink Model of Proposed Compensator with Conventional DC Link Controller

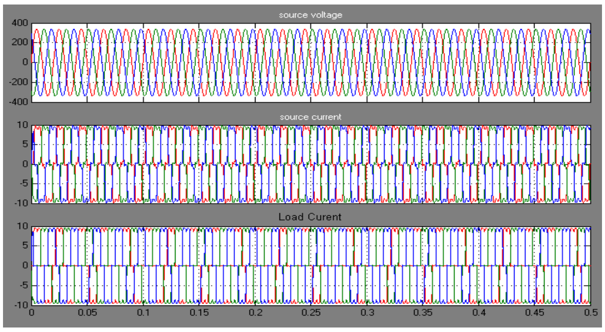

Figure 13: Source Voltage, Source Current, Load Current without Compensator

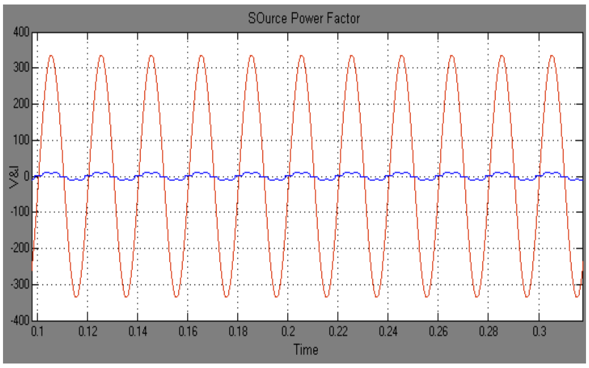

Figure 14: Source Power Factor

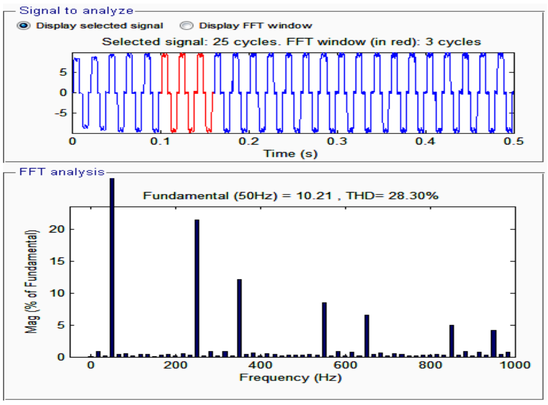

Figure 15: FFT Analysis of Source Current without Compensator

Figure 15 shows the FFT Analysis of source current without compensator, we get THD is 28.30%.

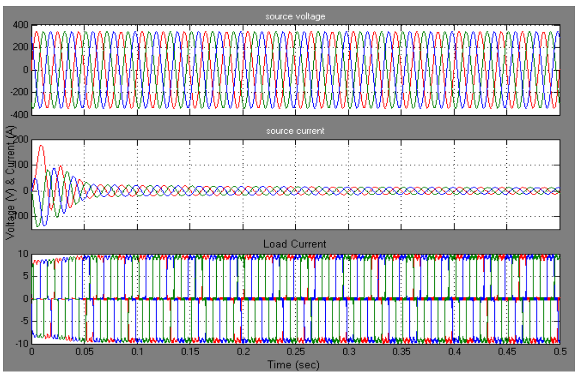

Figure 16: Source Voltage, Source Current, Load Current with Conventional Based Compensator

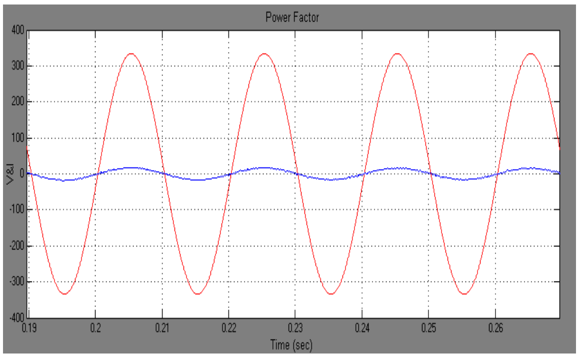

Figure 17: Source Power Factor

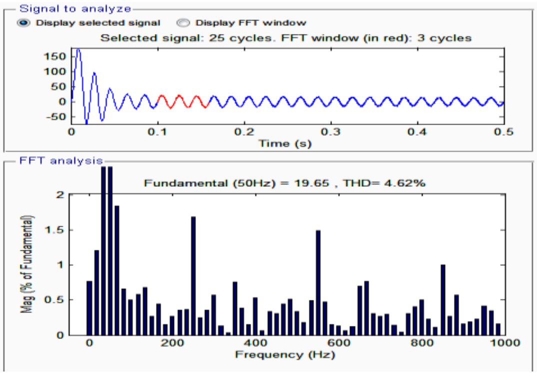

Figure 18: FFT Analysis of Source Current with Compensator

Figure 18 shows the FFT Analysis of source current with compensator, we get THD is 4.62%.

Case 2: Grid Connected PV System with proposed Fuzzy Logic Controller based Active Power Filter.

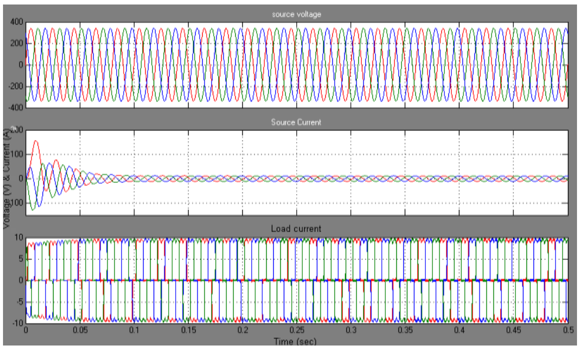

Figure 19: Source Voltage, Source Current, Load Current with Conventional Based Compensator

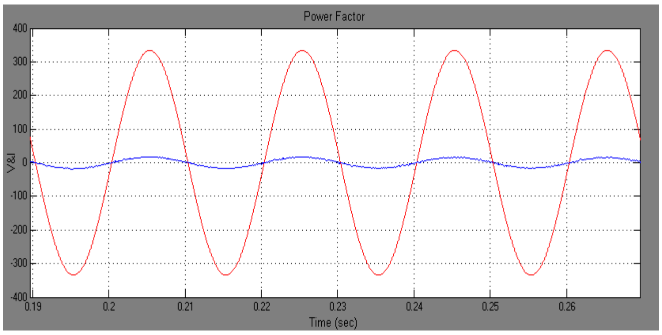

Figure 20: Source Power Factor

Figure 20 shows the source side power factor, is unity condition due to compensator is active.

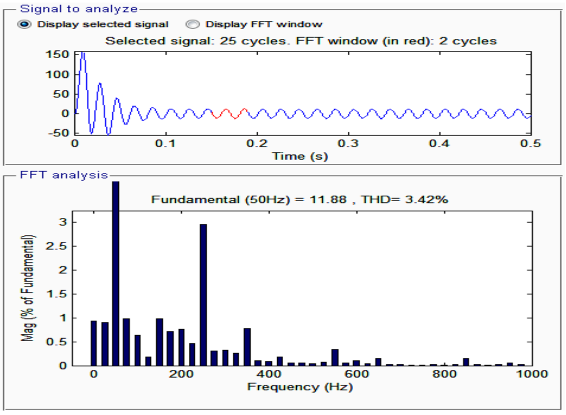

Figure 21: FFT Analysis of Source Current with Compensator

Figure 21 shows the FFT Analysis of source current with compensator, we get THD is 3.42%.

CONCLUSIONS

Classical "renewable energy source-based systems" are passive generators, as they produce maximal (non-dispatched) power even though this power is not useful for the grid. In this paper, multi functional grid interactive PV system is presented using a novel fuzzy logic based MPPT. The proposed MPPT controller is able to track the MPP accurately under uniformly varying as well as rapidly changing insulation and gives faster convergence as a variable step size in duty ratio is applied inherently by the algorithm and also used at our dc link controller for getting fast response. The proposed fuzzy controller maintains the dc link voltage within the limit for injecting the power into the grid. Apart from injecting active power during day time, the PV inverter also compensates the harmonics and reactive power during day time as well as at night. The simulation results validate the performance of grid interactive PV system for both active power injection as well as shunt active power filter functionality to mitigate the power quality issues thus increases the utilization factor of the system.

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